Development of a Framework of Research Topics in Systems Engineering

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Abstract. This paper describes the method and result of developing a framework of research topics in systems engineering. The framework of research topics was developed as part of a project to develop a vision for research in systems engineering for use by INCOSE. This paper also describes the relationship of the framework of research topics and the description of the future of systems engineering presented in the INCOSE document: *Systems Engineering Vision 2020*. This paper shows significant agreement between the structure of systems engineering described in the *Vision 2020* document and the framework developed in the vision for research in systems engineering. The processes used to develop both structures of ideas were conducted independently and were quite different. The agreement between them demonstrates the strength of the conclusion.

Introduction

During 2008 a decision was made that INCOSE Technical Operations, with the leadership of the author, would develop a vision for research in systems engineering which would provide guidance to researchers and prospective researchers. The purpose of the work was to list a set of research topics and to organize them into a form which make reasonable sense within the current understanding of systems engineering and expectations of the future development of the field. The purpose of the work is to stimulate research work to develop systems engineering by providing ideas in a form and framework which is accessible. In no way does the author intend to limit or restrict the range of research topics which are investigated, and so while an attempt at comprehensiveness and balance has been made, no absolute claim of either is asserted. This work is to be read as a contribution to the dynamic of the develop of systems engineering.

This paper describes the method used to develop the framework of research topics in systems engineering presented by the author in the vision for future systems engineering research document for INCOSE. The purpose of the vision for research document is to provide short and medium term goals for research in systems engineering. It is intuitively obvious that any such document, seeking to provide an outline of future research areas for a whole field of practice runs a significant risk of appearing to be a jumbled collection of items. Therefore, it was essential to provide order through developing an organizing framework of the topics.

The topics identified in the research vision document may be suitable for various stakeholders in the systems engineering community to investigate, including the academic community, industry, government and professional societies. Some topics may be more appropriate for certain stakeholders than others. This paper presents the background of the relationship of research in systems engineering and the practice of systems engineering; an explanation of the framework applied to the research topics; the research topics organized according to the framework; and a discussion of the inter-relation of the topics identified in the framework and the earlier INCOSE document: *Systems Engineering Vision 2020* (2006).

The problem of classification of entities into a framework is related to the fundamental theoretical problem of measurement. Measurement represents the observed state of nature by a value on a scale. The process of measurement maps the observed to the scale using a homomorphic transformation which results in the possibility of states of nature that are different being represented by the same scale value. The quality of a measurement scale, or the instrument used to perform the measurement, depends on the number of observed states of nature and the fineness of resolution required in order to make the distinctions between the states of nature that are necessary in the circumstances of the particular measurement. In turn this depends on the purpose for which the measurement is done, that is what cases need to be distinguished on the scale in order to provide a suitable foundation for the action that is to be taken as a result of the knowledge obtained through the measurement. If the resolution of the instrument is too coarse, too many states of nature map to the same scale value which results in insufficient ability to distinguish cases which matter from each other. If the resolution is too fine cases which should usefully be associated with each other are separated and interpretation of the measured data becomes difficult.

The classification of a framework can be considered as the mapping of observable entities to a nominal scale (Stevens 1946). If the framework is too fine grained there are too many groups and the cases are not usefully grouped with the result that the ordering effect of a framework is not achieved. Conversely, if the framework is too coarse grained too many entities are placed in the same group, resulting in insufficient information being yielded through the framework. While there is no absolute, quantitative, measure of the quality of a framework, the fuzzy categories of ‘good’, ‘poor’, ‘useful’ and ‘useless’ do provide a basis for judging the framework.

Background

Systems engineering originated soon after World War II when engineered products increased in complexity, particularly as a result of the installation of electronic equipment in a manner deeply embedded in the capability of the total product system. The terminology “systems engineering” appears to have been first used in telecommunications (Kelly 1950). The problems of building large scale telecommunications systems were important drivers in the development of holistic engineering analysis methods (Ferris 2007). Through the 1950’s the ‘systems engineering method’ was described in a broad-brush manner, emphasizing that engineers should take an holistic perspective to the investigation, design and analysis of proposed systems in contrast to an equipment and technology level focus (Ferris 2007). Initially, the major focus of systems engineering appeared to be any engineering work, but later the range of fields narrowed, largely to the defense and aerospace sectors, where systems engineering has remained prominent since.

It would appear that the linkage between systems engineering and these industry sectors developed during the 1950’s with the growth of the 1947 USAF Weapon Systems Management initiative into a DoD acquisition methodology which required systems engineering to be performed in a DoD approved manner. The idea of a DoD approved manner of doing systems engineering was not in the earliest, embryonic, form of systems engineering evidenced from the early 1950’s, which simply emphasized the need for engineering design work to take a whole of product system, and whole of lifecycle, approach. The earliest form, when described as project processes, sounds like a codification of the practices which had previously been associated with successful projects.

The DoD approved manner of doing systems engineering was reinforced by the development of MIL-STD-499, and successor standards listed in Sheard and Lake (2004), which further separated systems engineering from other engineering project methods used in commercial industry, and the separation of defense and commercial industries was reinforced through, amongst other things, the different approach to codified project process.

The approach to standards has changed from prescription to that found in ISO 15288 (ISO/IEC 2002), which introduced a higher level of abstraction that outlines the areas of concern for effective systems engineering, but did not detail the process to do the work. Thus, ISO 15288 represents a shift from specificity of action to identification of the matters of importance. This shift provides flexibility to find the most appropriate manner of working. This flexibility provides the opportunity for three things:

1. The exploration of new methods, potentially more effective, for achieving the desirable goal of reliably producing the most appropriate system for the need;
2. The opportunity to explore the applicability of systems engineering to the development of means to provide services, involving development of product systems and/or the application of existing product systems, and
3. The release of systems engineering from particular DoD acquisition processes which have alienated many in commercial industry from the use of systems engineering.

In turn, this deshackling of systems engineering from a particular set of processes opens the possibility for, and demands, research to determine the most appropriate methods for the design of systems in a variety of domains and situations. The complexity of current systems development, and the increasing incorporation of substantial legacy systems into systems of systems presents new design issues, which in turn demand further research.

Research and a Discipline

We consider now the relation between a field of practice and research that develops that field of practice because a discussion of research topics is, inherently a discussion of means to develop knowledge in a field of practice. Systems engineering is a discipline or field of practice concerned with the development of engineered systems which are most usually characterized as either technical or socio-technical systems. Some contributors also suggest that systems engineering provides a method to address needs where the solution may not involve a technical system as either the whole or part of the solution.

Checkland and Holwell (1998) describes a discipline as requiring three fundamental elements, a framework of ideas, F, a methodology for the practice of the discipline, M_1, and an area of concern in which the work of the discipline is done, A. Applying this to systems engineering the three elements are:

- The area of concern, the engineering of product systems that satisfy the sponsor's needs;
- The framework of ideas which is the accumulated body of knowledge of what can be done and when it is appropriate to do certain actions; and
- The methodology for working in the area of concern, the set of methods and processes which have been developed to practice systems engineering.

Cropley *et al* (2005) extended this construct as shown in Figure 1 wherein methodology M_1 represents the normal practice of the discipline and the second methodology, M_2, is the methodology for developing the framework of ideas of the discipline. The latter is the research methods appropriate for use in the discipline. Anyone who wishes to contribute to the framework of ideas of the discipline must use a method selected from the "recognized" set of research methods.

A given set of the elements depicted in Figure 1 represents a paradigm, as described by Kuhn (1970), because the framework of ideas incorporates the worldview of the discipline and that framework leads to the formulation of the two methodologies. The worldview also influences the perception of the area of concern held by practitioners. Kuhn argues that disciplines proceed for a time with incremental progress refining their framework of ideas and methodologies until, eventually, the structure becomes untenably complex. Then someone develops a new theory which provides a much simpler framework which adequately describes the facts known about the field. Kline (1995) adds that a discipline also has a group of paid scholars or participants. We note that this group may be wedded to the prevailing paradigm, and therefore seek to maintain the status quo of the field along with their existing professional esteem.

Figure 1 distinguishes two methodologies, M_1 and M_2, shown entirely separately, giving the impression they are two totally separate methodologies. This interpretation is not helpful. All practice in a field either does the work of the discipline or creates insight into the field. However, most action provides some of each outcome. The two methodologies distinguish the emphasis in the purpose for which the activity is done.

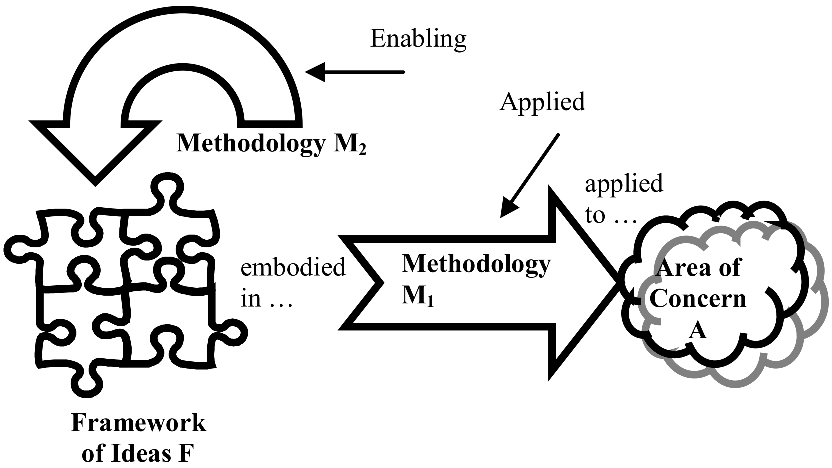

Figure 1. The relationship of the elements of a discipline (Cropley, Sproles et al. 2005).

List of Research Topics

The author solicited views concerning research needs in systems engineering from the members of the INCOSE Technical Operations team and received inputs from these and some other people to whom the original addressees of the author's request forwarded the request. The intention was to obtain input from a broad range of perspectives using an accessible and justifiable email list. The contributors are listed in the acknowledgements section of this paper. This section groups the research issues received from these contributors and further issues identified by the author from published sources: Axelbrand (2006), Blanchard and Fabrycky

(2006), Friedenthal (2006), Friedman (2006), Jackson (2006) and *Vision 2020* (INCOSE 2006). The author emphasizes that these people contributed ideas, most of which appear in this paper, but that the author may have reworded some items and that the author bears responsibility for the form and content of the research vision document and this paper. Through the project additional inputs have been solicited or obtained, using methods similar to those that produced the original list, and added to later versions of the work without any attempt to insert the additional items into superseded versions of the framework. Such an attempt is regarded as nugatory.

The research topics obtained from the various sources were first grouped according to the headings which the author used in the communication of request for input. The headings in the request for input chosen in the attempt to prompt respondents to think as broadly as possible across matters of immediate interest to speculative "blue sky" topics of longer term value. The topic headings provided as prompts were: "grand themes", "appropriate methodology", "useful research projects", and "research consequent upon findings of the above".

The topics acquired were grouped by the author under these headings to produce Table 1. The Table 1 framework joined many disparate topics and scattered ideas related to particular subjects across the headings. As a result the framework of Table 1 did not separate items which would be usefully separated and did not group items which would be usefully grouped. Consequently the framework of Table 1 was judged to be a 'poor' framework, and a better alternative was sought.

A new framework was devised phenomenologically. The topics obtained from the contributors and other sources were grouped, based on their inherent similarity of subject matter, using a conceptual clustering approach. The clusters that resulted were reviewed to propose headings which were descriptive of the set of items already clustered. The outcome was the framework of Table 2 below. In the process of developing the second framework some additional topics were added to the list, resulting in the larger set in Table 2 than in Table 1. The additional topics were introduced as a result of either further thinking about the issues or obtaining input from additional contributors or sources.

Relation to INCOSE Vision 2020

In this section a comparison between the INCOSE *Systems Engineering Vision 2020* (2006) and the set of research topics, organized in the framework of Table 2 is presented. Figure 1 of *Vision 2020* (2006) describes the predicted future form of systems engineering in five dimensions. The five dimensions are: global environment; nature of present and future systems; systems engineering processes; modeling and tools including model-based systems engineering; and education and research. The linking of "education" and "research" in a single heading is, if the "and" in the heading is regarded as a simple conjunction, a combination of two unlike elements, and if the "and" is understood hendiadycly becomes a fifth kind of entity of a different kind to the others, which leaves the impression that the "education and research" is somewhat disconnected from the other four headings which clearly relate to systems engineering practice. In either case it would appear that the intention is to separate into one category the systems engineering activities which happen in the academy from the activities which occur in the work of engineering real stuff.

The authors of *Vision 2020* also note several themes being confronted and anticipated in the current and expected environment for systems engineering (2006). These themes relate to the issues of: complexity; scale; scope; impact of national, natural and cultural environments; and legacy systems. Challenges to development and broadening of interest in systems engineering

Table 1. The first framework of research topics presenting the topics elicited in personal communications and from published sources.

1. Grand Themes

a. What is systems engineering?
b. What do systems engineers do in the workplace?
c. What is a systems engineer?
d. To what extent are "people skills" required by systems engineers to be effective?
e. To what extent are defined processes, e.g. as captured in IDEF0, sufficient?
f. Both the immediately above involve enterprise architectures.
g. Design of systems to ensure resilience: avoidances, survival and recovery.
h. How can holistic and analytical methods be combined to provide useful system insights?
i. Systems Enterprise Product Architecture lifecycle transition to modeling, simulation and stimulation.
j. Managing complexity via organizational architecture (minimizing communication interfaces) via SE basics.
k. SE during the end-phases of lifecycle – i.e. production, maintenance, disposal, environmental impact and proactive planning.
l. Who is the 'real' customer of systems engineering – the employer, some broader community – and what implications this has for systems engineers?
m. Means to consistently integrate matters additional to the hardware and software design into the systems engineering activity in a balanced manner.
n. Methods to address the issues arising from legacy systems in the design of new or updated systems.
o. Methods of addressing systems of systems.
p. Methods to improve systems architecting work.
q. Development of automated and model based methods in place of use of textual processes and requirements.
r. Means to incorporate disparate stakeholder views in systems engineering process.
s. Model Based Systems Engineering to support predictive and effects based processes.
t. Development of culturally and process sensitive approaches to systems engineering.
u. Is a Grand Unified Theory of Systems Engineering either possible or necessary. How can systems engineering be viewed coherently in the absence of such a theory.

2. Appropriate Methodology

a. Is there a demonstrably sound methodology to assess the quality of enabling systems?
b. Is there optimum process architecture?
c. What are Technical Performance Measures of the effectiveness and efficiency of systems engineering processes?
d. How are, and should, processes be defined and controlled? What implications does this have for the outcome of a systems engineering effort?
e. The effect of and means to deal with non-stationary project environments.
f. Case studies of the effect of current resilience related methodologies.
g. Development of systems engineering methodology implementing the principles of Lean Engineering – focus on satisfying the customer with 'perfection' and ensuring efficient and effective engineering methods.
h. How can systems engineering methodology address the 'community level' effect of the products of the engineering effort? (Examples of applications include issues such as utility design.)
i. Processes to deal with the complexities introduced through multi-party teams.
j. Can systems engineering processes be treated as modular or do they need to be considered only as coherent sets of processes?
k. Means for end-to-end validation of systems engineering processes to ensure that the right system is made.
l. Means to ensure that systems engineering processes are 'life cycle complete' – i.e. include all downstream phases.

3. Useful Research Projects

a. How do the existing processes, and standards, compare with respect to management and effectiveness of the systems engineering effort?
b. What is complexity, what is emergent behavior, are emergent behaviors designed in, what fundamentally causes emergent behaviors?
c. Is a new kind of systems engineer needed to deal with complexity?
d. Resilience and the 'iceberg theory' – near misses and accidents are closely associated. How does this enable one to measure system resilience?
e. Resilience and optimization of enterprise funding allocations.
f. Identification and use of heuristics that indicate resilience related issues.
g. Use of Open Systems Development Reference Model and the use of UML for Open Distributed Processing systems.
h. Investigation of what can be achieved in Network Centric Operations.
i. Means to predict and to design human intensive systems. A study of the interaction of people, human-error and disasters is needed.

4. Research Consequent on the Findings of the Above

a. What are the inferences of the above for enabling systems?
b. What are the inferences of the above for systems engineering education?
c. Who are the stakeholders of systems engineering education?
d. What content should be taught in systems engineering education?
e. What is the most appropriate pedagogy to maximize learning?
f. How can one teach students to apply systems thinking to problems?

Table 2. The phenomenologically constructed framework of research topics.

1. Defining the systems engineering task a. What is systems engineering? b. What do systems engineers do in the workplace? c. Systems engineering during the end-phases of lifecycle – i.e. production, maintenance, disposal, environmental impact and proactive planning. d. Who is the 'real' customer of systems engineering – the employer, project principal, a broader community – and what implications does this have for systems engineers? e. Is a Grand Unified Theory of Systems Engineering either possible or necessary? How can systems engineering be viewed coherently if such a theory is absent. f. What research methods are appropriate, and for what purposes, in systems engineering? g. What is the relationship between systems engineering and the systems sciences? h. How can the knowledge of the systems sciences be applied in the systems engineering task? i. What is the range of product systems and service development projects for which systems engineering is applicable? j. Are there projects or problem domains to which systems engineering should not be applied? k. Definition of F, the framework of ideas of Systems Engineering, in particular the science that informs systems engineering.	**2. Holism in systems engineering** a. Design of systems to ensure resilience: avoidances, survival and recovery. b. How can holistic and analytical methods be combined to provide useful system insights? c. Means to consistently integrate matters additional to the hardware and software design into the systems engineering activity in a balanced manner. d. Resilience and the 'iceberg theory' – near misses and accidents are closely associated. How does this enable one to measure system resilience? e. Resilience and optimization of enterprise funding allocations. f. Identification and use of heuristics that indicate resilience related issues. g. Case studies of the effect of current resilience related methodologies. h. How can systems engineering methodology address the 'community level' effect of the products of the engineering effort? (Examples of applications include issues such as utility design.) i. Means for end-to-end validation of systems engineering processes to ensure that the right system is made. j. What are appropriate means to incorporate the holistic perspective in project developing minor product systems (e.g. typical consumer products)? k. Means to ensure that systems developed are capable of providing the intended service effect. l. What is complexity, what is emergent behavior, are emergent behaviors designed in, what fundamentally causes emergent behaviors? Is a new kind of systems engineer needed to deal with complexity?
3. Education a. To what extent are "people skills" required by systems engineers to be effective? b. What are the inferences of the existing processes, and standards with respect to the management and effectiveness of the systems engineering effort for systems engineering education? c. What are the inferences of whether there is an optimum model for systems engineering education? d. What are the inferences of Technical Performance Measures of the effectiveness and efficiency of systems engineering processes for systems engineering education? e. What is a systems engineer? (Building on work begun by Heidi Davidz and Moti Frank.) f. What are the personal attributes and knowledge required for successful practice in systems engineering? g. Is there a desirable psychological profile for systems engineering practice? h. Who are the stakeholders of systems engineering education? i. What content and skills should be taught in systems engineering education? j. What is the most appropriate pedagogy to maximize learning? k. How can one teach students to apply systems thinking to problems? l. How can one ensure that systems engineering graduates have the appropriate combination of knowledge, skills, attributes and attitudes for successful practice in systems engineering, and how can one assess attainment of those qualities?	**4. Model-based methods** a. Systems Enterprise Product Architecture lifecycle transition to modeling, simulation and stimulation. b. Development of automated and model based methods in place of use of textual processes and requirements. c. Model Based Systems Engineering to support predictive and effects based processes. d. Use of Open Systems Development Reference Model and the use of UML for Open Distributed Processing systems. e. The possibility, suitability, applicability and nature of other system modeling languages. f. How can Model Based methods be made scalable across a range of product and project sizes?
5. Process/Standards a. To what extent are defined processes, e.g. as captured in IDEF0, sufficient? b. Methods to improve systems architecting work. c. How do the existing processes, and standards, compare with respect to management and effectiveness of the systems engineering effort? (continued next page)	**6. Organizational architecture** a. Managing complexity via organizational architecture (minimizing communication interfaces) via SE basics. b. Development of culturally and process sensitive approaches to systems engineering. c. Resilience and optimization of enterprise funding allocations. (continued next page)

d. Is there an optimum process architecture? e. What are Technical Performance Measures of the effectiveness and efficiency of systems engineering processes? f. How are, and should, processes be defined and controlled? What implications does this have for the outcome of a systems engineering effort? g. Development of systems engineering methodology implementing the principles of Lean Engineering – focus on satisfying the customer with 'perfection' and ensuring efficient and effective engineering methods. h. Processes to deal with the complexities introduced through multi-party teams. i. Can systems engineering processes be treated as modular or do they need to be considered only as coherent sets of processes? j. How can processes and standards be developed in order to provide smooth scalability across the range of possible project sizes. k. What processes can be used to ensure the system developed suitable provides the service for which it is developed? l. Means to incorporate disparate stakeholder views in systems engineering process. m. Means to ensure that systems engineering processes are 'life cycle complete' – i.e. include all downstream phases.	d. Is there a demonstrably sound methodology to assess the quality of enabling systems? e. Is there an optimum organizational architecture? f. What are Technical Performance Measures of the effectiveness and efficiency of systems engineering organizational architectures? g. Are there predictive measures of project performance which can be applied early to predict project outcome? h. What is required in order to appropriately scale organization architecture for organizational size? i. What is required to introduce systems engineering into commercial enterprises and other non-traditional application areas?
7. Systems of systems and legacy systems a. Methods to address the issues arising from legacy systems in the design of new or updated systems. b. Methods of addressing systems of systems. c. What are the characteristics of the various kinds of system of system scenarios including the effect of factors such as scale, time to place in service, classes of pre-existing systems, amount of new work to be done etc.? d. The issues of system documentation and configuration control in system of systems situations. e. What approaches are most effective in planning and managing the evolution of large-scale capabilities such as transport, global real-time information systems, defense, etc. f. Investigation of what can be achieved in Network Centric Operations. g. Means to ensure assurance that a system of systems will deliver the capability intended.	**8. Sundry other matters** a. Means to predict and to design human intensive systems. A study of the interaction of people, human-error and disasters is needed. b. The effect of and means to deal with non-stationary project environments. c. Making systems engineering relevant in the 21st Century – e.g. sought after by decision-makers in social and economic as well as technological problem domains.

identified in *Vision 2020* include: evolution of systems engineering standards; concurrent engineering; distributed teams; perception of systems engineering as overhead heavy; concept of process maturity; development of model-based methods; overly ambitious adoption of systems engineering methods; inconsistencies between practice in the field and education; rapid technological change; changes in the demographics of society; and globalization.

The recognition of the future needs in systems engineering is expressed:

> Systems engineering must support architecting, design, development, production and sustainment, recognizing that the future brings opportunities and increased complexity and associated needs for evolution and adaptation as societies and businesses become increasingly inter-twined (INCOSE 2006).

This quotation indicates appreciation of the growth required in systems engineering and the need for research relating to the deeply enmeshed web of issues described by the dimensions, themes and challenges, as itemized above.

The second half of *Vision 2020* (2006) identifies a range of matters about which new knowledge will be required for development and implementation of the broader visions of system architecture including the technical and non-technical aspects of systems development and the development of model-based systems engineering. These matters were significant contributors to the increase in the number of research topics between the two frameworks.

A basis for judging the quality of the framework of Table 2 is required. The judgment which is useful in this context is whether the framework provided in Table 2 is reasonable in the context of the existing state of knowledge, practice and expectations for the future in systems engineering. In the development of a framework of research topics which are not claimed to be exhaustive and definitive, only a guide to researchers about the kinds of topics which it useful to investigate it is not worthwhile to expend significant effort to attempt to prove that the framework suggested here is either necessarily perfect or the best possible. The test applied is the much lighter test of whether the framework is reasonable and provides a useful organization of topics to encourage research.

This framework was generated using the topic elicitation and conceptual clustering processes described above to construct the framework of topics. Table 1 shows the relation of the research topics, listed by their numerical and letter references in Table 2, in relation to the five dimensions of the future form of systems engineering provided in *Vision 2020*.

Table 3 and Figure 2 show that the taxonomy presented in Table 2, above, results in a reasonably simple and elegant relation to the five dimensions presented in *Vision 2020* (INCOSE 2006) which was developed independently.

Table 3. Relation of the five dimensions of systems engineering in *Systems Engineering Vision 2020* (INCOSE 2006) and the research topic taxonomy of Table 2.

***Systems Engineering Vision 2020* (INCOSE 2006) dimension**	**Taxonomy topics**
Global environment	1.c, 1.d 8.b, 8.c
The nature of present and future systems	7.a, 7.b, 7.c, 7.d, 7.e, 7.f, 7.g 8.a
Systems engineering processes	2.a, 2.b, 2.c, 2.d, 2.e, 2.f, 2.g, 2.h, 2.i, 2.j, 2.k, 2.l 5.a, 5.b, 5.c, 5.d, 5.e, 5.f, 5.g, 5.h, 5.i, 5.j, 5.k, 5.l, 5.m 6.a, 6.b, 6.c, 6.d, 6.e, 6.f, 6.g, 6.h, 6.i
Modeling and tools including model-based systems engineering	4.a, 4.b, 4.c, 4.d, 4.e, 4.f
Education and research	1.a, 1.b, 1.e, 1.f, 1.g, 1.h, 1.i, 1.j, 1.k 3.a, 3.b, 3.c, 3.d, 3.e, 3.f, 3.g, 3.h, 3.i, 3.j, 3.k, 3.l

The link pattern in Figure 2 is simple, with no overlapping lines, although the mapping between the framework of Table 2 and the categories of *Vision 2020* is many-to-many rather than one-to-one. The figure has been simplified by ordering the titles of the five dimensions and the eight groups in the framework to avoid any link lines crossing. Changing the order of the groups in the framework to avoid crossing of link lines is permissible because the groups are only nominal categories, following the description of measurement scales of Stevens (1946), with no information conveyed through any order in which they may be placed as there would be in the other types of measurement scale.

The fact that it was possible to avoid crossing of link lines in Figure 2 indicates a simple relation between the two independent organizations of the systems engineering space. This link pattern indicates that in some cases the natural grouping of research topics identified through the elicitation process described above, seeking to obtain broad community input, and thus to avoid missing major areas of interest, may map closely to a single dimension of the future of systems engineering, as described in *Vision 2020*. In other cases one of the dimensions in *Vision 2020* has been divided into several identifiable groups. This division is useful in that it provides a higher level of organization of topics associated with the particular dimension. The three topic groups: "Process/Standards"; "Organizational architecture"; and "Holism in systems engineering"; contain 34 of the total of 73 topics, i.e. 46% of the total set. A single group in a set of 5 groups which combines over 45% of the total number of elements is too coarse a structure to provide useful insight into the subject matter. The division of this group into the three smaller groups is useful.

The fact that over 45% of the topic areas identified relate to systems engineering processes is unsurprising given the emphasis that this area of interest receives in the community. It is useful to provide subdivision of this area to enable more specific discussion of the issues associated with it.

The majority of the research topic areas pertain to matters that are perceived as important in the current paradigm of systems engineering. This fact is entirely to be expected. The Kuhnian discussion of research in a field, as described above, presents a chronology of research in any field (Kuhn 1970). The chronology follows the pattern:

1. A paradigm is established;
2. Research seeks to refine knowledge within the paradigm and to complete the understanding through building on the foundational premises of the paradigm;
3. Difficulties are encountered which result in the theory becoming excessively complex; and
4. Someone proposes a new theory which explains all the current knowledge in a unified and coherent manner, again providing the desired simplicity, and this theory becomes the new paradigm.

In systems engineering there is an established structure of theory and practice which presents a number of felt need points related to what are essentially refinements of the current situation. In addition there are several areas of current activity which have the potential to introduce radical changes to the theory and practice of systems engineering. An example of such an area of investigation is the strong emphasis on model-based systems engineering, which may, depending on the direction in which this work is taken and the extent to which it is pursued, fundamentally challenge the traditional construct of requirements-based systems engineering.

There are some topics, such as 1.a: "What is systems engineering?" which should not be misunderstood as trivial topics. These topics are questions which are currently appearing in the community, and express a desire for a profound answer which will provide guidance into a number of the other topics addressing issues such as the areas of concern for which systems engineering is applicable and may prompt further creative ideas that may radically transform practice just as the current interest in model-based systems engineering appears capable. To date much of the practice of systems engineering has been associated with the development of technical systems, and more recently socio-technical systems, with emphasis on design of the system conceived as some kind of object or product. Some of the research topics follow from current questioning concerning the applicability of systems engineering for designing services, which are not objects or products. This area presents challenges related to the limits of the capability of systems engineering and the modifications to systems engineering theory and practice required to support service design.

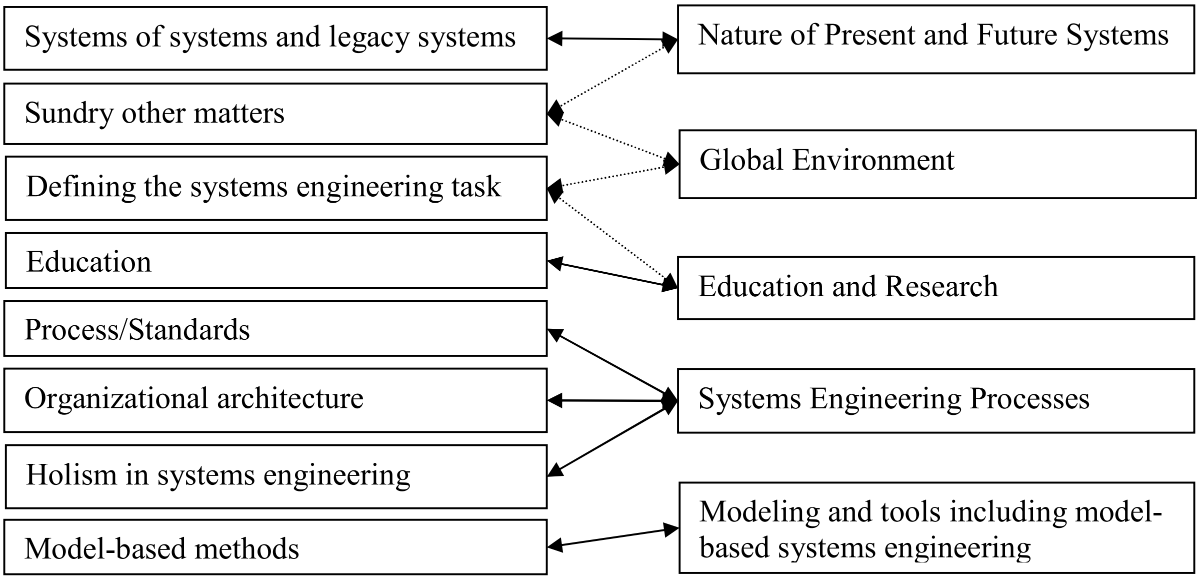

Figure 2. Visual presentation of the relation of the five dimensions and the research topics in the taxonomy of Table 2. Solid link lines indicate whole set mapping from the eight topic areas to the five dimensions. Dotted lines indicate that a topic area maps to more than one of the five dimensions.

Conclusions

This paper has described the process of eliciting research topics from a representative sample of the systems engineering community. The emphasis in the question process was their beliefs about future research needs, not past or current achievements. These topics were then organized into a framework using a conceptual clustering technique. The resulting framework was then compared with the *Vision 2020* (INCOSE 2006) with the demonstration of a close relation between the framework developed in this work and the independent set of dimensions of systems engineering.

The majority of the research topics identified were concerned with subject matter which would lead to improvement of systems engineering theory and practice within the current paradigm, but there were a number of topics offered which address subject matter which significantly challenges the current paradigm and which could, therefore lead to creation of a new paradigm of theory and practice.

The balance of many topics seeking to refine current theory and practice and some topics addressing foundational issues or approaches with potential to significantly challenge current theory and practice is an indication that systems engineering stands in a position where the community of practitioners feels a need for a major paradigmatic event, either to profoundly complete and confirm the current paradigm or to establish a new paradigm.

The fundamental goal of systems engineering is to enable the reliable engineering of systems that provide profound and appropriate solutions to the needs which prompted the engineering projects. There is an established method for doing systems engineering work which has prompted a significant number of research topics. The findings of research work addressing these topics should lead to significantly improved practice and achievement, whether that practice remains within the current paradigm or represents a new paradigm for systems engineering.

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Biography

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